PCT

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification [7] : G02B 6/17, 6/16, C03B 37/075, 37/027	**A1**	(11) International Publication Number: **WO 00/49436** (43) International Publication Date: 24 August 2000 (24.08.00)

(54) Title: IMPROVEMENTS IN OR RELATING TO PHOTONIC CRYSTAL FIBRES

(57) Abstract

A photonic crystal fibre comprising a bulk material having an arrangement of longitudinal holes (130, 140) and a guiding core (135), wherein the fibre has at–most–two–fold rotational symmetry about a longitudinal axis and as a result of that lack of symmetry, the fibre is birefringent.

- 1 -

Improvements in or relating to photonic crystal fibres

This invention relates to photonic crystal fibres and
to a method of producing photonic crystal fibres.

5   A photonic crystal fibre is a special form of optical
fibre. Optical fibres are used in many fields including
telecommunications, laser machining and welding, laser beam
and power delivery, fibre lasers, sensors and medical
diagnostics and surgery. They are typically made entirely
10   from solid transparent materials such as glass and each
fibre typically has the same cross-sectional structure along
its length. The transparent material in one part (usually
the middle) of the cross-section has a higher refractive
index than the rest and forms an optical core within which
15   light is guided by total internal reflection. We refer to
such a fibre as a standard fibre.

       Single-mode optical fibres are preferred for many
applications because of their superior wave-guiding
properties. However, even so-called single-mode optical
20   fibres do not generally offer adequate control over the
polarisation of propagating light. A single-mode fibre is
so called because it supports only one transverse spatial
mode at a frequency of interest, but that spatial mode
exists in two polarisation states; that is two degenerate
25   modes that are polarised in orthogonal directions. In real
fibres, imperfections will break the degeneracy of those
modes and modal birefringence will occur; that is, the mode
propagation constant β will be slightly different for each
of the orthogonal modes. Because the modal birefringence
30   results from random imperfections, the propagation constants
will vary randomly along the fibre. In general, light
introduced into the fibre will propagate in both modes and
will be coupled from one to the other by small bends and

- 2 -

twists in the fibre. Linearly polarised light will be
scrambled into an arbitrary polarisation state as it
propagates along the fibre.

In order to maintain the polarisation of a mode in a
5   standard fibre, birefringence can be deliberately introduced
into the fibre (so that the effective indices of the two
polarisation modes are different) in order to render
insignificant the effects of small imperfections. If light
is linearly polarised in a direction parallel to one of the
10 optic axes of the fibre then the light will maintain its
polarisation. If it is linearly polarised at some other
angle, the polarisation will change, as the light propagates
down the fibre, from linear to elliptical to linear (not
parallel to the starting polarisation) to elliptical and
15 back to linear again, with a period known as the beat

length, L_B, where $L_B = \dfrac{2\pi}{|\beta_x - \beta_y|}$ and β_x and β_y are the

propagation constants of the orthogonal modes. That
variation is a consequence of a phase difference between two
orthogonal components of the mode, which results from the
20 difference in their propagation constants. The shorter the
beat length, the more resilient is the fibre to
polarisation-scrambling effects. Typically, conventional
polarisation-preserving fibre has a beat length of the order
of a millimetre. The strength of birefringence can also be

25 represented by the parameter $B = \dfrac{|\beta_x - \beta_y|}{k_0} = |n_x - n_y|$, where

$k_0 = \dfrac{2\pi}{\lambda}$ (where λ is the wavelength) and n_x and n_y are the

refractive indices seen by the orthogonal modes.

In the last few years a non-standard type of optical
fibre has been demonstrated, called the photonic-crystal
30 fibre (PCF). Typically, this is made from a single solid,

- 3 -

and substantially transparent, material within which is
embedded a periodic array of air holes, running parallel to
the fibre axis and extending the full length of the fibre.
A defect in the form of a single missing air hole within the
5 regular array forms a region of raised refractive index
within which light is guided, in a manner analogous to
total-internal-reflection guiding in standard fibres.
Another mechanism for guiding light is based on photonic-
band-gap effects rather than total internal reflection.
10 Photonic-band-gap guidance can be obtained by suitable
design of the array of air holes. Light with particular
propagation constants can be confined to the core and will
propagate therein.

Photonic-crystal fibre can be fabricated by stacking
15 glass canes, some of which are capillaries on a macroscopic
scale, into the required shape, and then holding them in
place while fusing them together and drawing them down into
a fibre. PCF has unusual properties such as the ability to
guide light in a single-mode over a very broad range of
20 wavelengths, and to guide light having a relatively large
mode area which remains single-mode.

Birefringence can be produced by several mechanisms.
It can be caused by the anisotropic nature of the
polarisability of a material; i.e. by anisotropy at an
25 atomic level. It can be caused by the arrangement of
elements of a material structure at a scale larger than
atomic; that phenomenon is known as form birefringence. It
can also be caused by mechanical stress; that phenomenon is
known as stress birefringence or the photo-elastic effect.
30 In standard fibres, form birefringence is achieved by
changing the shape of the fibre cross-section; for example,
by making the core or cladding elliptical. Birefringence in
a weakly-guiding fibre is generally rather weak ($B \sim 10^{-6}$).

- 4 -

Stress birefringence can be induced by inserting rods of
borosilicate glass on opposite sides of the fibre core in
the fibre pre-form. Variation in the location and shape of
the borosilicate rods can induce different levels of
5 birefringence. Stress-induced birefringence permits B-10^{-4}.

The methods used to produce birefringence in standard
fibres, and thus to produce standard polarisation-preserving
fibres, are, in general, not directly suitable for use in
photonic-crystal fibre.

10 An object of the invention is to provide a photonic
crystal fibre which is birefringent so that the fibre can be
used as a polarisation-preserving fibre. Another object of
the invention is to provide a method of producing such a
fibre.

15 According to the invention there is provided a photonic
crystal fibre comprising a bulk material having an
arrangement of longitudinal holes and a guiding core,
wherein the fibre has at most-two-fold rotational symmetry
about a longitudinal axis (that is any longitudinal axis)
20 and as a result of that lack of symmetry, the fibre is
birefringent.

The arrangement of holes may be substantially periodic
except for the presence of the core.

Advantageously, the birefringence is such that light
25 with a wavelength of 1.5 microns propagating in the fibre
has a beat length of less than 1 cm. More advantageously,
the birefringence is such that light with a wavelength of
1.5 microns propagating in the fibre has a beat length of
less than 5 mm. More advantageously, the birefringence is
30 such that light with a wavelength of 1.5 microns propagating
in the fibre has a beat length of less than 1 mm and
preferably less than 0.5 mm; such short beat lengths are not
generally obtainable in standard fibres. Of course, a

- 5 -

particular fibre may not guide light at a wavelength of 1.5
microns; in that case, the beat length at a guided
wavelength may be readily scaled up or down to an equivalent
beat length at 1.5 microns. For example, a beat length of
5   1mm at a wavelength of 1.55 microns is equivalent to a beat
length of 0.41mm at a wavelength of 633nm, and a beat length
of 0.5mm at a wavelength of 1.55 microns is equivalent to a
beat length of 0.21mm at a wavelength of 633nm.

        It will be understood that in a real fibre there will
10   inevitably be minor anomalies in the structure that mean
that no fibre has absolute symmetry of any kind; in
conventional photonic crystal fibres, however, it is readily
apparent that the real fibre does have a considerable amount
of rotational symmetry (most commonly six-fold rotational
15   symmetry) and that symmetry is sufficiently strong to make
the behaviour of the fibre similar to that of a theoretical
fibre having absolute symmetry. In a similar way, where
reference is made to a fibre having at-most-two-fold
rotational symmetry, it should be understood that not only
20   does the fibre not strictly have any higher symmetry but,
furthermore, it does not behave as would a fibre which had a
significant amount of higher symmetry.

        In its broadest aspect, the invention is concerned with
a lack of higher rotational symmetry in any aspect of the
25   fibre. Most typically, the lack of symmetry may arise in
some feature of the internal microstructure of the fibre
and, commonly, of the arrangement of holes, whilst the
overall cross-sectional shape of the fibre may be circular
and thus have circular symmetry; it is within the scope of
30   the invention for the arrangement of holes to have more-
than-two-fold rotational symmetry but for the fibre to lack
more-than-two-fold rotational symmetry in some other sense
and examples of such arrangements are given below.

- 6 -

Preferably, the fibre has two-fold rotational symmetry.

Preferably, the rotational symmetry is about an axis passing through the core.

If a fibre has greater than two-fold rotational
5   symmetry then linearly polarised light would have the same propagation constant β when polarised parallel to two or more (not necessarily orthogonal) axes. As is the case in a real fibre with circular symmetry, imperfections in the fibre will result in power transfer between modes polarised
10   parallel to each of those axes. Consequently, light which is initially linearly polarised will excite additional modes and quickly become randomly polarised.

The core may include a hole. The hole may be filled with material other than air. Alternatively, the core may
15   not include a hole.

The arrangement of holes may have at-most-two-fold rotational symmetry parallel to the longitudinal axis of the fibre. Alternatively, the arrangement of holes may have higher-than-two-fold rotational symmetry about an axis
20   parallel to the longitudinal axis of the fibre. The rotational symmetry may be about an axis passing through the core.

The lack of higher rotational symmetry may at least partly result from a variation, across the cross-section of
25   the fibre, in one or more of the following: the microstructure of the core, the diameter of the holes, the bulk material, the material contained in the holes or the shape of the holes. The shape variation may be due to deformation resulting from stresses in the fibre as it is
30   drawn. The lack of higher rotational symmetry may result from a variation across the cross-section of the fibre, in one of the following in combination with one or more of the following or with a variation in another parameter: the

- 7 -

microstructure of the core, the diameter of the holes, the
bulk material, the material contained in the holes, the
shape of the holes.

The birefringent fibre may have form birefringence
5 and/or stress birefringence. Although form birefringence in
standard fibres is not sufficient to give the required short
beat length, the potentially much larger refractive index
contrast in photonic crystal fibres can result in strong
form birefringence. A new effect, not possible with
10 standard fibres, is found when the pattern of stresses
within the fibre during the draw process distorts certain of
the air holes surrounding the fibre core along one axis,
giving additional birefringence.

Also according to the invention, there is provided a
15 method of producing a birefingent photonic crystal fibre,
the method comprising the following steps:

    (a)   forming a stack of canes, at least some of which
            are capillaries, the stack including canes
            arranged to form a core region in the fibre and
20   canes arranged to form a cladding region in the
            fibre; and

    (b)   drawing the stack of canes into a birefringent
            fibre, which has at-most-two-fold rotational
            symmetry about a longitudinal axis.

25 Birefringence is thus introduced by modification of the
method used to fabricate the photonic crystal fibre preform.
The modification of the fabrication procedure may consist of
the reduction in material symmetry to at-most-two-fold
symmetric features in the periodic stack of canes which
30 comprise the preform. Such structures will, in general,
change both the shape of the guided mode and the pattern of
stresses within the photonic crystal structure.

One way in which birefringence can be introduced is by
including in the preform different capillaries at two-fold
symmetric pairs of lattice sites. Those inclusions might be
placed near to the core so as to alter the shape of the

5   guided mode ("form birefringence") or they might be placed
some way from the core but be made of a material with
different properties, thus altering the pattern of stresses
within the fibre core ("stress birefringence"). The preform
may be structured so as to introduce birefringence by

10   forming substantial parts of the fibre preform from a
different type of capillary, which again introduces both
stress and form birefringence. The basic periodic lattice
which forms the waveguide cladding could be a simple close-
packed array of capillaries with nominally identical

15   external diameters or it could be an array of capillaries
with generally different morphological characteristics, and
forming different periodic structures. A square lattice may
be formed from capillaries and rods with different
diameters. Square and rectangular lattices can be used to

20   build up naturally birefringent crystal structures for the
cladding, simplifying the design of polarisation-preserving
photonic crystal fibre.

The lack of higher rotational symmetry may at least
partly result from variations, across the cross-section of

25   the stack, in the internal diameters of the capillaries, in
the material of which the canes are made, in the material
with which the capillaries are filled and/or in the external
diameter of the canes.

Canes may be provided at the vertices of a cladding

30   lattice which has at-most-two-fold rotational symmetry about
the centre of the canes arranged to form the core.
Capillaries of selected internal diameters may be provided
at the vertices of a cladding lattice which has at-most-two-

- 9 -

fold rotational symmetry about the centre of the canes
arranged to form the core, the selected diameters of the
capillaries at the vertices of the cladding lattice being
different from the diameters of the capillaries at other

5   sites.

A substantial number of cladding canes, near to the
canes arranged to form the core, may be different.

Birefringence may at least partly result from stresses
formed within the fibre as it is drawn. The stress may be

10   introduced by the inclusion, at sites having at-most-two-
fold rotational symmetry, of a cane made from a different
material from that of which at least some of the other canes
in the lattice are made. The stress may be introduced by the
inclusion, at sites having at-most-two-fold rotational

15   symmetry, of capillaries having a different capillary wall
thickness from that of at least some of the other
capillaries.

The stresses may result in the deformation of holes
surrounding the core of the drawn fibre and that deformation

20   may result in birefringence.

The stresses may result in stresses in the core of the
drawn fibre and those stresses may result in birefringence.

The lack of higher rotational symmetry may at least
partly result from pressurisation and/or evacuation of at

25   least one of the capillaries during the drawing of the
stack.

In any of the above-described methods, the rotational
symmetry of the stack of canes is preferably two-fold
rotational symmetry.

30   Also according to the invention there is provided a
method of producing a photonic crystal fibre, comprising:

(a)   providing a plurality of elongate canes, each
having a longitudinal axis, a first end and a

second end, at least some of the canes being
capillaries each having a hole parallel to the
longitudinal axis of the cane and running from the
first end of the cane to the second end of the

5   cane;

(b)   forming the canes into a stack, the canes being
arranged with their longitudinal axes
substantially parallel to each other and to the
longitudinal axis of the stack;

10   (c)   drawing the stack into a fibre whilst maintaining
the hole of at least one capillary in
communication with a source of fluid at a first
pressure whilst maintaining the pressure around
the capillary at a second pressure that is

15   different from the first pressure, wherein the
hole at the first pressure becomes, during the
drawing process, a size different from that which
it would have become without the pressure
difference.

20   In the new method, substantial and controlled changes
may occur in the fibre structure while it is being drawn;
for example, there may also be controlled expansion of the
air holes during the draw. In prior art photonic crystal
fibres the required microstructure was created on a

25   macroscopic scale, and then reduced in scale by drawing it
into a fibre.

Preferably, the tube surrounds the stack of canes over
at least a part of their length and the inside of the tube
is maintained at the second pressure.

30   It will be understood that the phrase "expansion of the
air holes" refers to production of air holes of a size (in
cross-section taken perpendicularly to the longitudinal axis
of the capillaries) greater than that which it would have

been without the pressure difference. In reality, a fibre produced by drawing has a very much smaller total cross-sectional area than the preform (here the stack of canes) from which it is made, and the air holes in the invention

5   will therefore not, in general, "expand" in absolute terms.

Changes during the draw can be thus controlled in two main ways: by use of a pressure differential applied to certain holes, and by enclosing the entire preform, preferably in a tube which is preferably thick walled and

10   may comprise silica and is drawn down with and forms part of the final fibre. Preferably the tube does not undergo deformation significantly different from that which it would undergo without the pressure difference.

Preferably the tube restricts the expansion of at least

15   one of the holes at the first internal pressure.

Preferably the stack of canes has at-most-two-fold rotational symmetry about any of the longitudinal axes. Such a stack may be used in the drawing of a birefringent fibre.

20   Preferably during the drawing process:

the tube is sealed to a first end of an evacuatable structure and the second end of the tube is within the evacuatable structure;

at least some of the capillaries pass through the

25   evacuatable structure and are sealed to a second end thereof;

and the evacuatable structure is substantially evacuated in order to produce the second internal pressure.

Preferably the evacuatable structure is a metal tube.

30   By way of example only, an embodiment of the invention will now be described, with reference to the accompanying drawings, of which:

- 12 -

Fig. 1 is a schematic diagram of an example of a standard fibre.

Fig. 2 is a schematic diagram of a conventional photonic-crystal fibre having a high-index core defect.

5   Fig. 3 is a schematic diagram of a conventional photonic-crystal fibre (a photonic-band-gap fibre) having a low-index core defect.

Fig. 4 is a schematic diagram of a photonic-crystal-fibre preform which has been partially drawn into a fibre.

10   Fig. 5 is a schematic cross-sectional diagram of a first polarisation-preserving photonic-crystal fibre according to the invention, in which the cladding holes form a rectangular lattice.

Fig. 6 is a schematic cross-sectional diagram of a

15   second polarisation-preserving photonic-crystal fibre according to the invention, in which the pattern of cladding holes near to the core has two-fold symmetry.

Fig. 7 is a schematic cross-sectional diagram of a third polarisation-preserving photonic-crystal fibre

20   according to the invention, in which the pattern of cladding holes far from the core has two-fold symmetry.

Fig. 8 is a schematic cross-sectional diagram of a fourth polarisation-preserving photonic-crystal fibre according to the invention, in which the pattern of

25   dielectric inclusions in the cores of the lattice has two-fold symmetry.

Fig. 9 is a schematic cross-sectional diagram of an arrangement of canes for forming a photonic crystal fibre having a square lattice.

30   Fig. 10 is a schematic cross-sectional diagram of a portion of a photonic crystal fibre having a square lattice of holes each having one of two different diameters.

- 13 -

Fig. 11 shows a photonic crystal fibre having a square lattice.

Fig. 12 shows canes forming part of a stack for forming a photonic crystal fibre.

Fig. 13 shows a photonic crystal fibre formed from a stack such as that shown in Fig. 12.

Fig. 14 shows schematically a stack of capillaries suitable for use in a further method according to the invention;

Fig. 15 shows schematically apparatus used with the stack of Fig. 14;

Fig. 16a shows the cleaved end face of a photonic crystal fibre made from a preform similar to that of Fig. 14 and with the apparatus of Fig. 15;

Fig. 16b shows a detail of the structure near the core of the fibre of Fig. 16a;

Fig. 17a shows a highly birefringent fibre made with the apparatus of Fig. 15;

Fig. 17b shows polarisation beating observed at a wavelength of 1550nm in the fibre of Fig. 17a.

Standard fibres, such as the example shown in Fig. 1, in their simplest form comprise essentially a cylindrical core 10 and concentric cylindrical cladding 20. Typically, both the core and the cladding will be made of the same material, usually silica, but each is doped with other materials in order to raise the refractive index of the core 10 and lower the refractive index of the cladding 20. Light, of appropriate wavelengths, is confined to the core 10, and guided therein, by total internal reflection at the core-cladding boundary 15.

A typical photonic crystal fibre, shown in Fig. 2, comprises a cylinder of transparent bulk material 30 (e.g.

silica) with a lattice of cylindrical holes 40, which run
along its length. The holes are arranged at the vertices
and centres of regular hexagons, which have six-fold
rotational symmetry. The holes have a regular period, broken
5   by the omission of one hole near the centre of the fibre.
The region 50 of the fibre surrounding the site of the
missing hole has the refractive index of the bulk material
30. The refractive index of the remainder of the fibre is
attributable to the refractive index of both the bulk
10   material 30 and the air in the holes 40. The refractive
index of air is lower than that of, for example, silica and,
consequently, the 'effective refractive index' of the
material with the holes is lower than that of the region 50
surrounding the missing hole. The fibre can therefore
15   confine light approximately to the region 50, in a manner
analogous to waveguiding by total internal reflection in
standard fibres. The region 50 is therefore referred to as
the 'core' of the photonic crystal fibre.

In another form of photonic crystal fibre, photonic
20   band gap guidance acts to confine light to the fibre 'core'.
In the example of such a fibre shown in Fig. 3, there is a
matrix of holes 70 in bulk material 30. The holes are
arranged at the vertices (but not the centres, cf. Fig. 2)
of regular hexagons, which have six-fold rotational
25   symmetry. The regularity of the matrix is again broken by a
defect, but it is, in the illustrated example, an additional
hole 60 at the centre of one of the lattice hexagons, that
hexagon being near the centre of the fibre. The area
surrounding the additional hole 60 can again be referred to
30   as the core of the fibre. Disregarding (for the moment)
hole 60, the periodicity of holes in the fibre results in
there being a band-gap in the propagation constants of light
which can propagate in the fibre. The addition of hole 60

- 15 -

effectively creates a region with a different periodicity,
and that region can support propagation constants different
from those supported in the rest of the fibre. If some of
the propagation constants supported in the region of hole 60
5   fall within the band-gap of propagation constants forbidden
in the rest of the fibre then light with those propagation
constants will be confined to the core and propagate
therein. Note that because the hole 60 is a low-index
defect (it results in air being where bulk material would
10 otherwise be), total internal reflection effects are not
responsible for that waveguiding in the illustrated example.

Photonic crystal fibres can be manufactured by a
process, one stage of which is shown in Fig. 4. In the
first stages of that process (not shown), a cylinder of bulk
15 material (e.g. silica), is milled so that it has a hexagonal
cross-section, and a hole is drilled along its centre. The
rod is then drawn into a cane using a fibre drawing tower.
The cane is cut into lengths and the resulting, short canes
80 are stacked to form an array of canes, as shown in Fig.
20 4. The cane 100 at the centre of the illustrated array is
not a capillary; i.e., it has no hole; the illustrated array
will form an effective-index guidance type of fibre. The
array of canes 80 is fused together and then drawn into the
final photonic crystal fibre 110.

25   The fibre shown in Fig. 5 has a lattice 120 of holes,
which are arranged at the vertices of rectangles, which are
not squares. The periodicity of the lattice is broken by
the omission of a hole in the region 125 near the centre of
the fibre cross-section. The centre-to-centre spacing
30 (pitch) of the holes is different parallel to axis x (pitch
Λ_x) from the pitch (Λ_y) parallel to axis y. The fibre shown
in Fig. 5 could be manufactured using a cane which is milled
to have a rectangular cross-section. The lattice of Fig. 5

has two-fold rotational symmetry and will therefore be
birefringent.

Figs. 6 and 7 show photonic crystal fibres which are
effective-index-guidance fibres having a hexagonal lattice
5   similar to that of the fibre of Fig. 2. Such lattices are
not intrinsically birefringent. However, in the lattices of
Fig. 6 and 7, holes 140 are of a larger diameter than holes
130. That anisotropy in the lattice creates a two-fold
rotationally symmetric pattern of holes about the region 135
10   where a hole is missing from the lattice.

The pattern of large holes 140 in Fig. 6 has an effect
analogous to that of form birefringence in a standard fibre.
The variation of hole diameter near to the 'core' 135
directly creates a variation in the effective index seen by
15   a guided mode.

The pattern of large holes 140 in Fig. 7 produces
stresses in the core which cause birefringence in the same
way that birefringence is caused in standard fibres. A new
effect, not possible with standard fibres, is that the
20   pattern of stresses within the fibre can, during the draw
process, distort some of the air holes surrounding the fibre
core 135 along one axis, giving additional birefringence.

Another alternative, illustrated in Fig. 8, is for some
of the holes 150 to be filled with material other than air
25   (so that they have a different dielectric constant). Again,
the six-fold rotational symmetry of the lattice is reduced
to a two-fold rotational symmetry.

The stack of canes shown in Fig. 9 are of three types:
large diameter canes 160 which are capillaries, small
30   diameter solid canes 170 and a large diameter solid cane
180. The canes are arranged so that the large diameter
canes 160 form a square lattice, which is broken by a defect
at a central site, the defect being the large diameter solid

cane 180.   Interstitial gaps, resulting from the non-
tesselating nature of the circular cross-sections of canes
160, are filled by small diameter canes 170.

     A photonic crystal fibre having two-fold symmetry is
5   shown in Fig. 10.   The fibre has a lattice structure which
     can be constructed from a stack of canes arranged in a
     manner similar to the stack of Fig. 9.   Solid cane 180
     results in a defect similar to defect 210.   In this case,
     however, alternate rows of holes (190, 200) have large and
10   small diameters respectively.   Such an effect could be
     achieved with the lattice of Fig. 9 by providing alternate
     rows of canes 160 with large and small internal diameters
     (but with constant external diameters).

     The fibre of Fig. 11 can be seen to have approximately
15   a square lattice such as might be produced from the stack of
     Fig. 9.

        Fig. 12 shows a stack of canes 220 which are
     capillaries.   The canes are arranged on an hexagonal
     lattice, with the periodicity of the structure broken by a
20   solid cane 240.   It will be noted that a row of canes about
     half-way up the photograph are capillaries with thicker
     walls 250 than the walls 230 of other capillaries.   When a
     fibre is drawn from the stack of canes, such an arrangement
     will result in a fibre, such as that shown in Fig. 13,
25   having a row of holes 260 having a smaller diameter than
     other holes in the fibre.

        Many other patterns of capillaries and canes, varying
     in various parameters, could be envisaged that would fall
     within the scope of the invention.

30   Another method of making a fibre is illustrated in
     figs. 14 and 15.   A stack of a regular array of capillaries
     300 are placed inside a thick-walled silica glass tube 310
     (Fig. 14).   The silica glass tube 310 forms part of the

- 18 -

fibre after drawing, serving as a jacket to provide
mechanical strength. During the drawing process (Fig. 15),
the inside of the tube 310 is evacuated by sealing it within
an evacuatable structure while the inside of some or all of
5 the capillaries 300 are kept at a different and higher
pressure, for example, because they are left open to the
atmosphere.

The evacuatable structure is a brass cylinder 320.
Initially it is open at both ends. The cylinder is then
10 sealed to the tube 310 at one end. The tube terminates
within the brass cylinder 320. Some or all of the
capillaries 300 pass right through the brass cylinder 320,
which is then sealed around those capillaries that pass
right through the cylinder at the top. The brass cylinder
15 320 is evacuated during the drawing process.

During the drawing process, in which the tube 310 and
the capillaries 300 are drawn downwardly from the brass
tube, the outer tube 310 does not collapse, despite being
evacuated, because it has thick walls. In contrast,
20 interstitial holes between capillaries 300 which are already
smaller and have relatively thin boundaries defined by walls
of the capillaries quickly collapse and are not present in
the final fibre (which is desirable). Capillaries which are
evacuated will also collapse completely if there is a higher
25 pressure around the capillary. On the other hand
capillaries which are filled with atmospheric-pressure air
expand.

By adopting the method just described it is possible to
form very regular and thin-walled structures and to make
30 fibres with very small guiding cores. Fig. 16 shows such a
fibre which has an outer cladding 330 comprising the tube
310 after drawing and an inner cladding 340 comprising the
capillaries 300. The inner cladding is of approximately

- 19 -

10μm radius and comprises a honeycomb structure of expanded holes. The holes surround a guiding core 350 that is of approximately 1μm diameter and has been formed from an elongate cane that is not a capillary. It will be

5. appreciated that the fibre shown in Fig. 16 is made by having all the capillaries 300 passing right through the cylinder 320 and has substantial multi-fold rotational symmetry; thus the fibre is not substantially birefringent.

In contrast Fig. 17a shows a fibre that is made to be

10 highly birefringent by stacking thicker-walled capillaries at certain sites; smaller air holes 360 are formed at those sites. An alternative method of producing the fibre might be by having four selected capillaries terminating within the cylinder 320; the holes in those selected capillaries 300

15 would not expand during drawing and would thereby provide the four small holes 360. The fibre of Fig. 17a is highly birefringent because it has only two-fold symmetry resulting from the four smaller holes 360 lying along a diameter of the inner cladding, either side of the core.

20 Fig. 17b shows the polarisation beating data of the fibre of Fig. 17a. From the data, the beat length of the fibre can be shown to be 0.92mm at a wavelength of 1550nm; such a beat length is sufficiently short for the fibre to act as a polarisation-maintaining, single mode photonic

25 crystal fibre.

- 20 -

CLAIMS

1. A photonic crystal fibre comprising a bulk material having an arrangement of longitudinal holes and a guiding core, wherein the fibre has at-most-two-fold rotational symmetry about a longitudinal axis and as a result of that lack of symmetry, the fibre is birefringent.

2. A photonic crystal fibre as claimed in claim 1, in which the arrangement of holes is substantially periodic except for the presence of the core.

3. A photonic crystal fibre as claimed in claim 1 or claim 2, in which the birefringence is such that light with a wavelength of 1.5 microns propagating in the fibre has a beat length of less than 5 mm.

4. A photonic crystal fibre as claimed in any preceding claim, in which the fibre has two-fold rotational symmetry.

5. A photonic crystal fibre as claimed in any preceding claim, in which the rotational symmetry is about an axis passing through the core.

6. A photonic crystal fibre as claimed in any of claims 1 to 5, in which the core includes a hole.

7. A photonic crystal fibre as claimed in claim 6, in which the hole is filled with material other than air.

8. A photonic crystal fibre as claimed in any of claims 1 to 5, in which the core does not include a hole.

9. A photonic crystal fibre as claimed in any preceding claim, in which the arrangement of holes has at-most-two-fold rotational symmetry about an

- 21 -

axis parallel to the longitudinal axis of the
fibre.

10. A photonic crystal fibre as claimed in any of
    claims 1 to 8, in which the arrangement of holes
    has higher-than-two-fold rotational symmetry about
    an axis parallel to the longitudinal axis of the
    fibre.

11. A photonic crystal fibre as claimed in any
    preceding claim, in which the lack of higher
    rotational symmetry at least partly results from a
    variation, across the cross-section of the fibre,
    in the microstructure of the core.

12. A photonic crystal fibre as claimed in any
    preceding claim, in which the lack of higher
    rotational symmetry at least partly results from a
    variation, across the cross-section of the fibre,
    in the diameter of the holes.

13. A photonic crystal fibre as claimed in any
    preceding claim, in which the lack of higher
    rotational symmetry at least partly results from a
    variation, across the cross-section of the fibre,
    in the bulk material.

14. A photonic crystal fibre as claimed in any
    preceding claim, in which the lack of higher
    rotational symmetry at least partly results from a
    variation, across the cross-section of the fibre,
    in the material contained in the holes.

15. A photonic crystal fibre as claimed in any
    preceding claim, in which the lack of higher
    rotational symmetry at least partly results from a
    variation, across the cross-section of the fibre,
    in the shape of the holes.

16. A photonic crystal fibre as claimed in claim 15, in which the shape variation is due to deformation resulting from stresses in the fibre as it is drawn.

17. A photonic crystal fibre as claimed in any preceding claim, in which the lack of higher rotational symmetry results from a variation across the cross-section of the fibre, in one of the following in combination with one or more of the following or with a variation in another parameter: the microstructure of the core, the diameter of the holes, the bulk material, the material contained in the holes, the shape of the holes.

18. A photonic crystal fibre as claimed in any preceding claim, in which the birefringent fibre has form birefringence.

19. A photonic crystal fibre as claimed in any preceding claim, in which the birefringent fibre has stress birefringence.

20. A method of producing a birefringent photonic crystal fibre, the method comprising the following steps:

    (a) forming a stack of canes, at least some of which are capillaries, the stack including canes arranged to form a core region in the fibre and canes arranged to form a cladding region in the fibre; and

    (b) drawing the stack of canes into a birefringent fibre which has at-most-two-fold rotational symmetry about any longitudinal axis.

21. A method as claimed in claim 20, in which the stack
    of canes is arranged to have at-most-two-fold
    rotational symmetry about a longitudinal axis of
    the stack.

22. A method as claimed in claim 20 or 21, in which the
    lack of higher rotational symmetry at least partly
    results from variations, across the cross-section
    of the stack, in the internal diameters of the
    capillaries.

23. A method as claimed in any of claims 20 to 22, in
    which the lack of higher rotational symmetry at
    least partly results from variations, across the
    cross-section of the stack, in the material of
    which the canes are made.

24. A method as claimed in any of claims 20 to 23, in
    which the lack of higher rotational symmetry at
    least partly results from variations, across the
    cross-section of the stack, in the material with
    which the capillaries are filled.

25. A method as claimed in any of claims 20 to 24, in
    which the lack of higher rotational symmetry at
    least partly results from variations, across the
    cross-section of the stack, in the external
    diameter of the canes.

26. A method as claimed in any of claims 20 to 25, in
    which canes are provided at the vertices of a
    cladding lattice which has at-most-two-fold
    rotational symmetry about the centre of the canes
    arranged to form the core.

27. A method as claimed in any of claims 20 to 25, in
    which capillaries of selected internal diameters
    are provided at the vertices of a cladding lattice
    which has at-most-two-fold rotational symmetry

- 24 -

about the centre of the canes arranged form the
core, the selected internal diameters of the
capillaries at the vertices of the cladding lattice
being different from the internal diameters of the
5   capillaries at other sites.

28.   A method as claimed in any of claims 20 to 27, in
       which a substantial number of cladding canes, near
       to the canes arranged to form the core, are
       different from a substantial number of cladding
10   canes, far from the canes arranged to form the
       core.

29.   A method as claimed in any of claims 20 to 28, in
       which the birefringence results at least partly
       from stresses formed within the fibre as it is
15   drawn.

30.   A method as claimed in claim 29, in which the
       stress is introduced by the inclusion, at sites
       having at-most-two-fold rotational symmetry, of a
       cane made from a different material from that of
20   which at least some of the other canes in the
       lattice are made.

31.   A method as claimed in claim 29, in which the
       stress is introduced by the inclusion, at sites
       having at-most-two-fold rotational symmetry, of
25   capillaries having a different capillary wall
       thickness from that of at least some of the other
       capillaries.

32.   A method as claimed in any of claims 29 to 31 in
       which the stresses result in the deformation of
30   holes surrounding the core of the drawn fibre and
       that deformation results in birefringence.

33.   A method as claimed in any of claims 29 to 31 in
       which the stresses result in stresses in the core

- 25 -

of the drawn fibre, and those stresses result in birefringence.

34. A method as claimed in any of claims 20 to 33, in which the lack of rotational symmetry at least partly results from pressurisation of at least one of the capillaries during the drawing of the stack.

35. A method as claimed in any of claims 20 to 34, in which the lack of rotational symmetry at least partly results from evacuation of at least one of the capillaries during the drawing of the stack.

36. A method as claimed in any of claims 20 to 35, in which the rotational symmetry of the stack of canes is two-fold rotational symmetry.

37. A method of producing a photonic crystal fibre, comprising:

    (a)   providing a plurality of elongate canes, each having a longitudinal axis, a first end and a second end, at least some of the canes being capillaries each having a hole parallel to the longitudinal axis of the cane and running from the first end of the cane to the second end of the cane;

    (b)   forming the canes into a stack, the canes being arranged with their longitudinal axes substantially parallel to each other and to the longitudinal axis of the stack;

    (c)   drawing the stack into a fibre whilst maintaining the hole of at least one capillary in communication with a source of fluid at a first pressure whilst maintaining the pressure around the capillary at a second pressure that is different from the first pressure, wherein the hole at the first

- 26 -

pressure becomes, during the drawing process,
a size different from that which it would
have become without the pressure difference.

38.   A method as claimed in claim 27, in which a tube
surrounds the stack of canes over at least a part
of their length and the inside of the tube is
maintained at the second pressure.

39.   A method as claimed in claim 38, in which the tube
restricts the expansion of at least one of the
holes at the first internal pressure.

40.   A method as claimed in any of claims 37 to 39, in
which the tube does not undergo deformation
significantly different from that which it would
undergo without the pressure difference.

41.   A method as claimed in any of claims 37 to 40, in
which, during the drawing process:

the tube is sealed near to the first end to a
first end of an evacuatable structure and the
second end of the tube is within the evacuatable
structure;

at least some of the capillaries pass through
the evacuatable structure and are sealed to a
second end thereof;

and the evacuatable structure is
substantially evacuated in order to produce the
second internal pressure.

42.   A method as claimed in claim 41, in which the
evacuatable structure is a metal tube.

43.   A method as claimed in any of claims 37 to 42, in
which the stack of canes has at-most-two-fold
rotational symmetry about any of the longitudinal
axes.

1/9
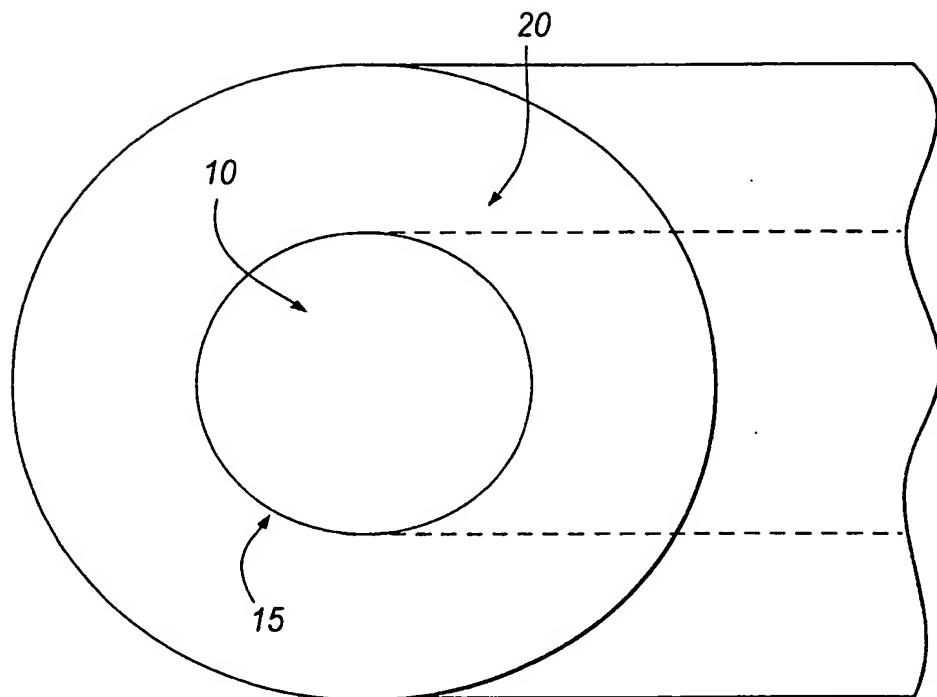
Fig.1

Fig.2

2/9
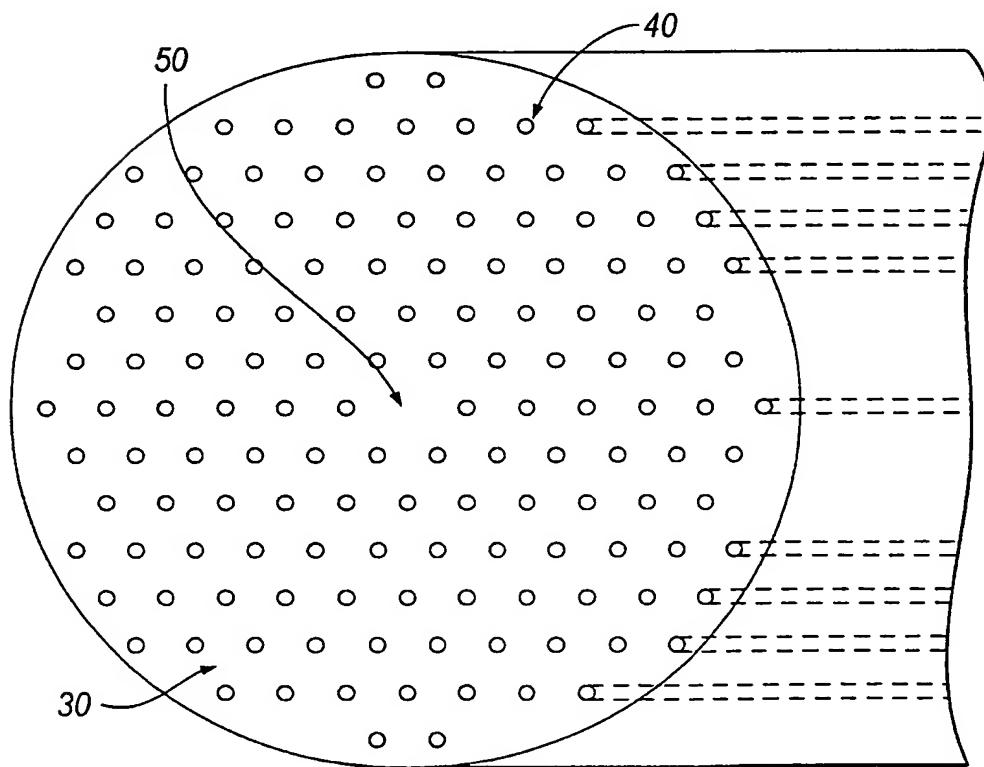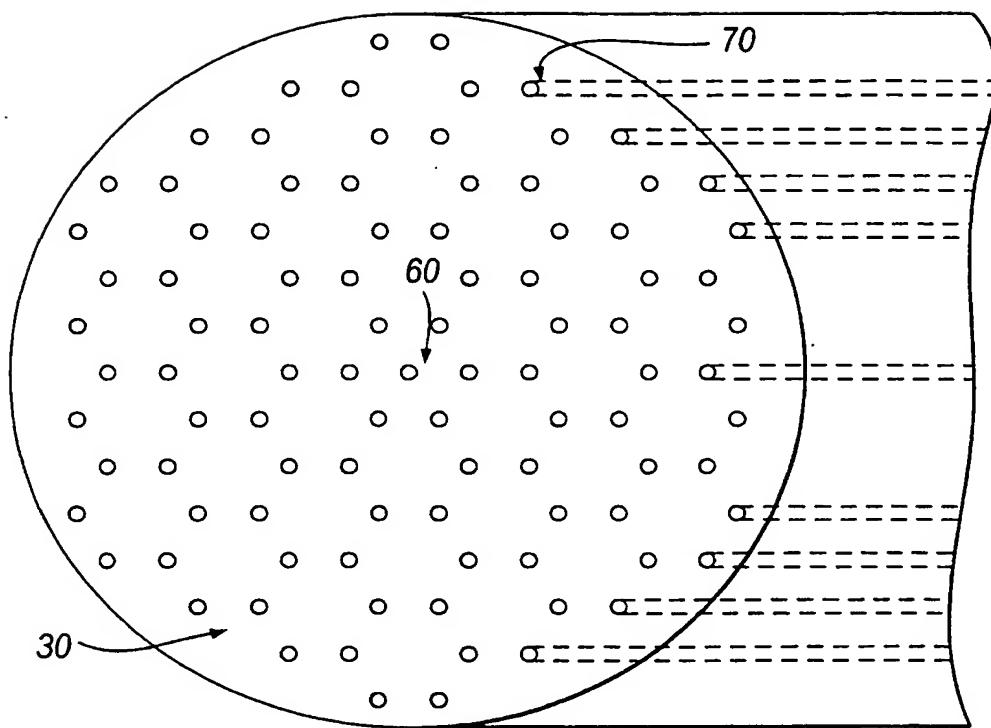
Fig.3
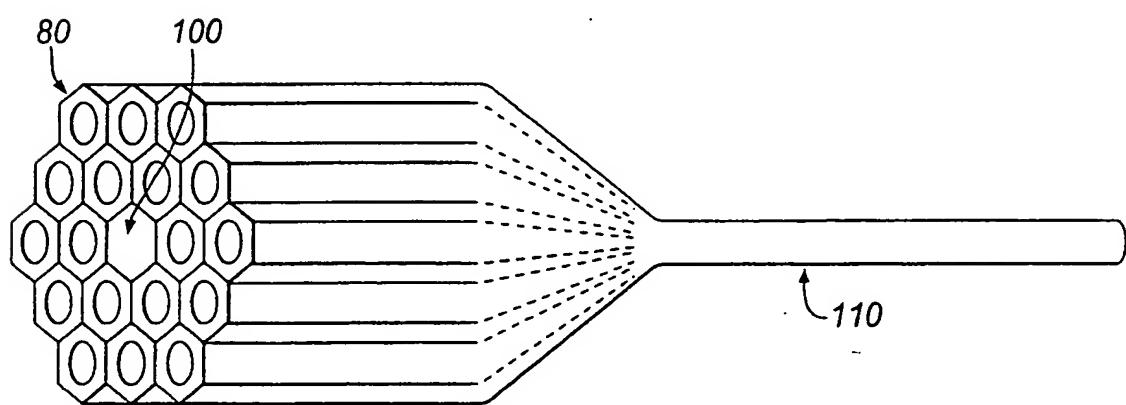
Fig.4
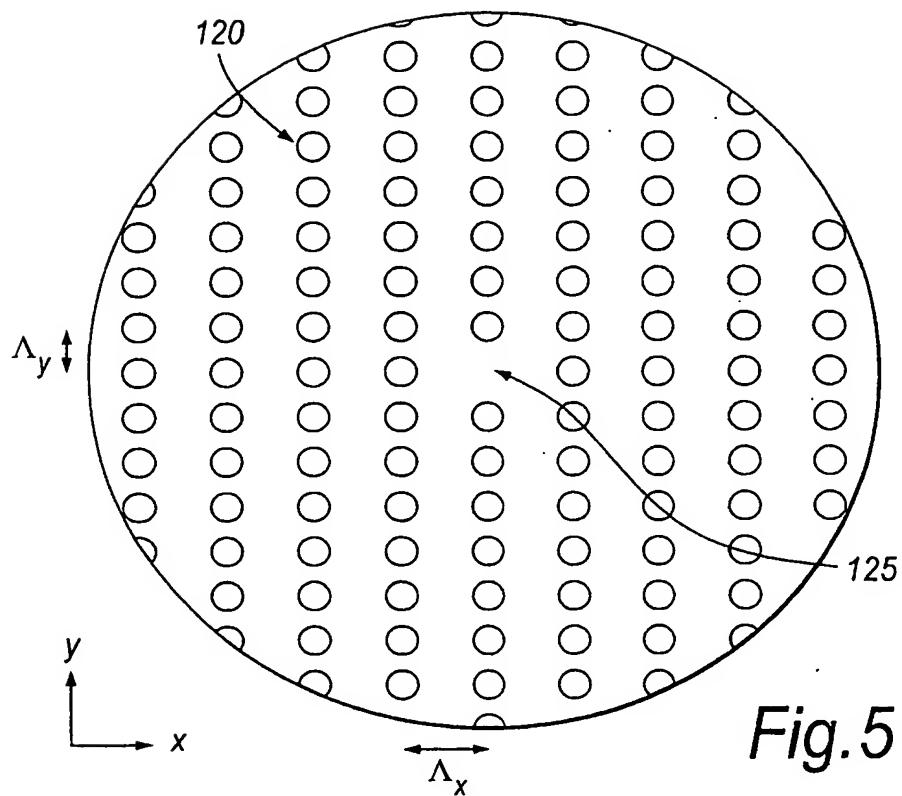
Fig.5

Fig.6

4/9

Fig.7

Fig.8

Fig.9

Fig.10

Fig.11

Fig.12

240
250
220
230

260
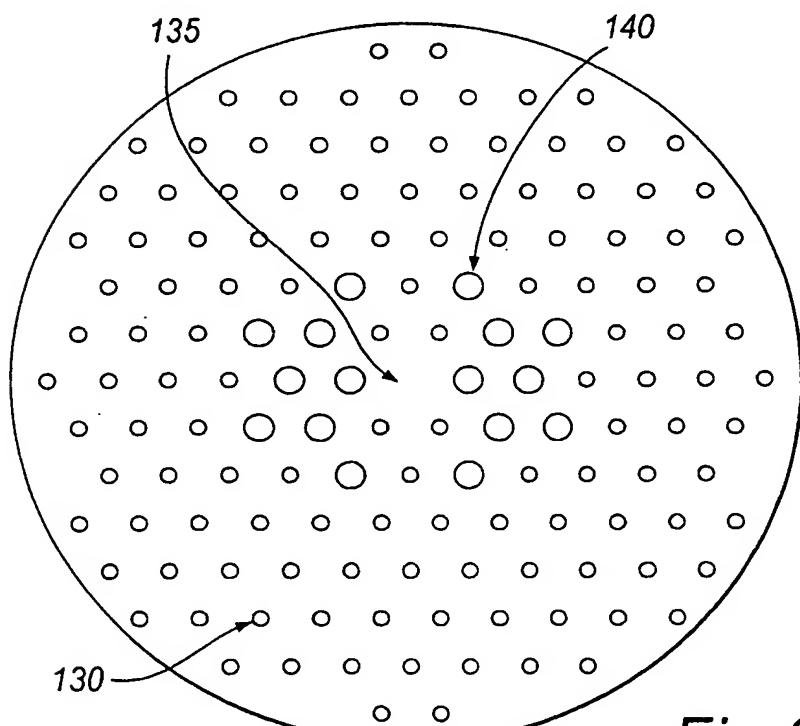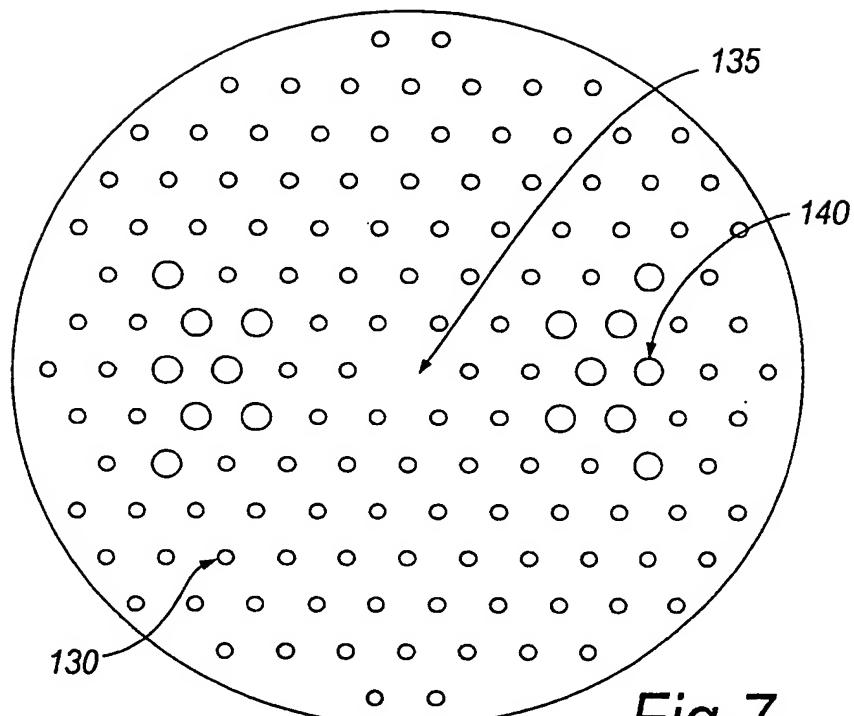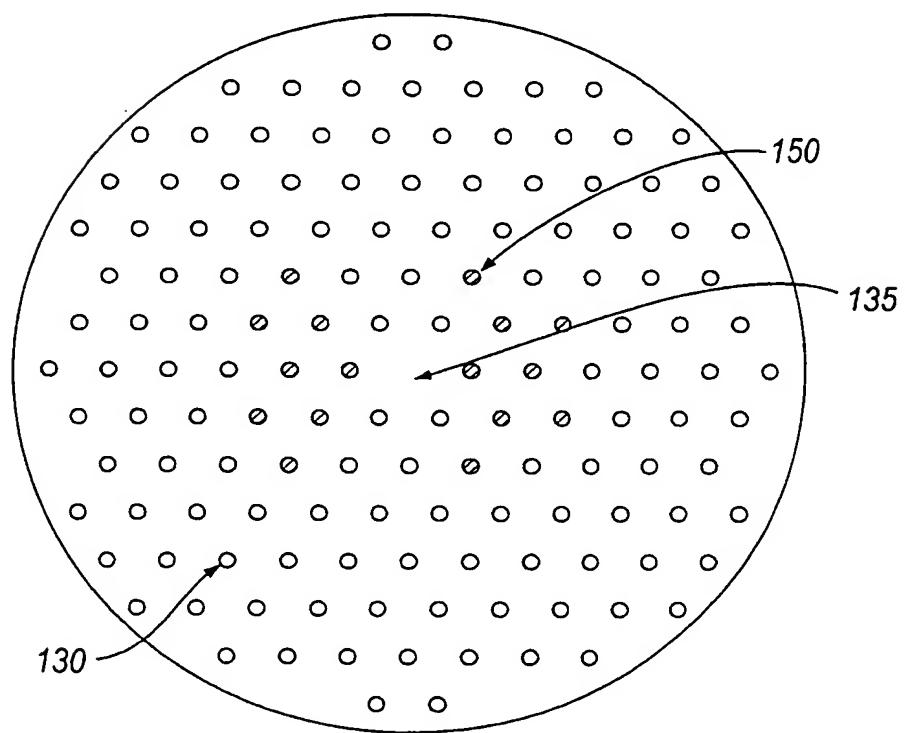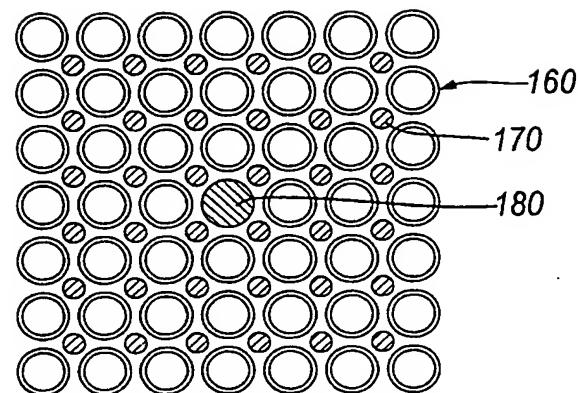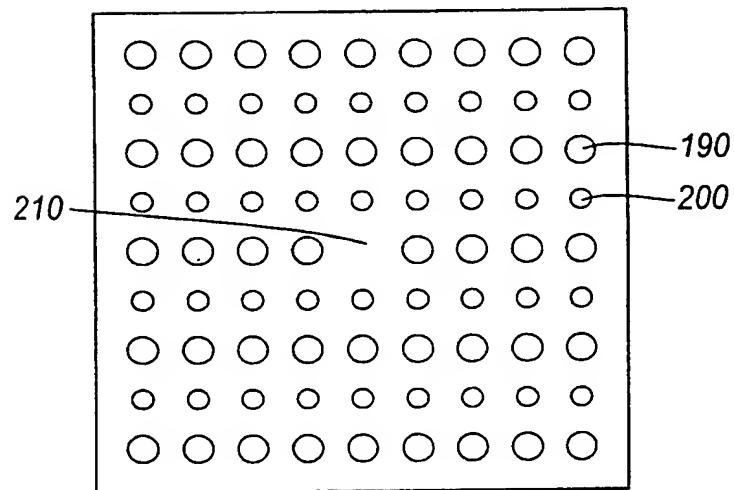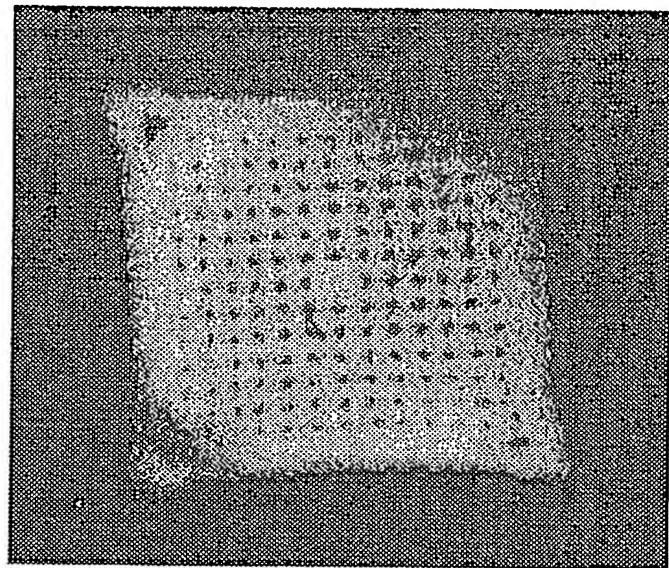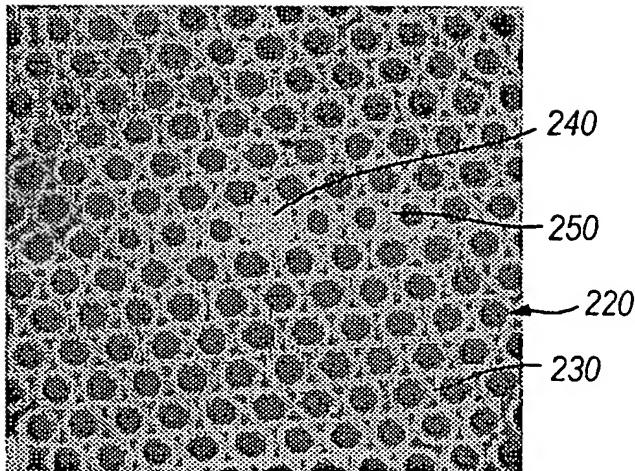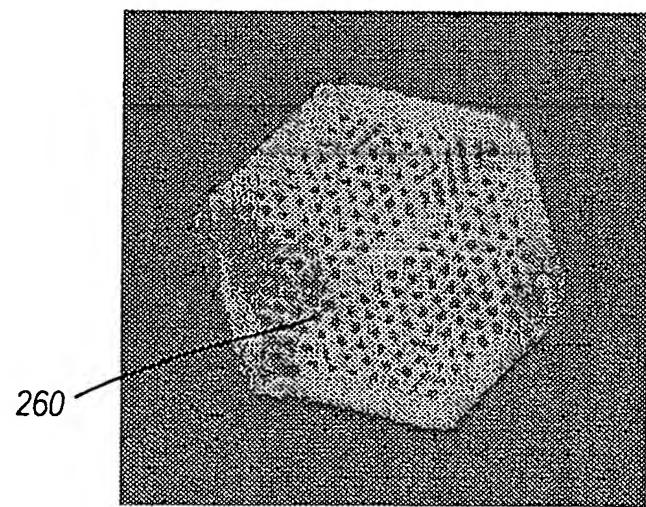
Fig.13

7/9
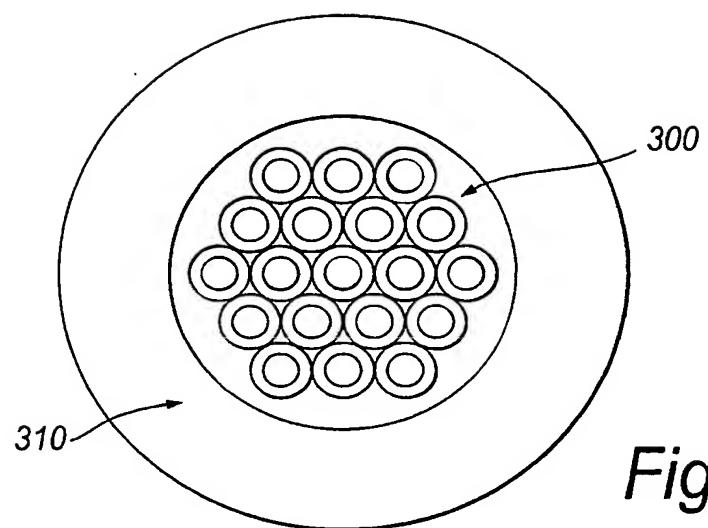
Fig.14
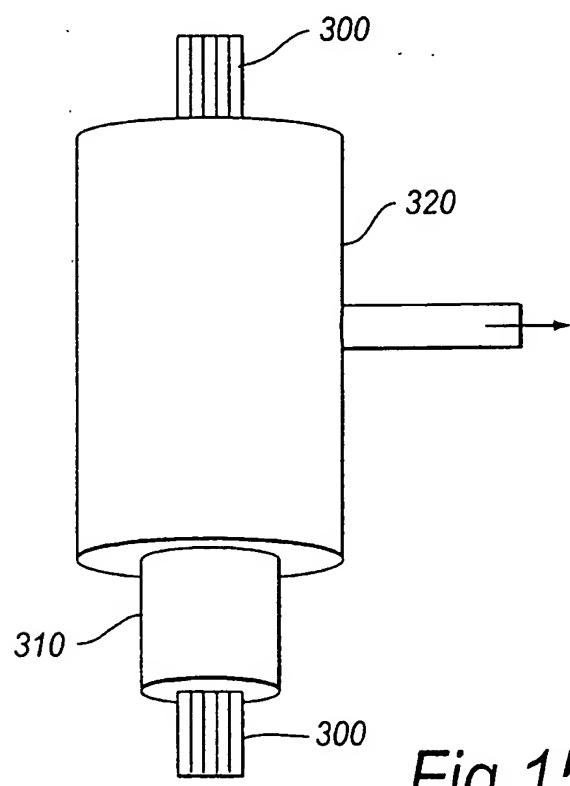
Fig.15

8/9
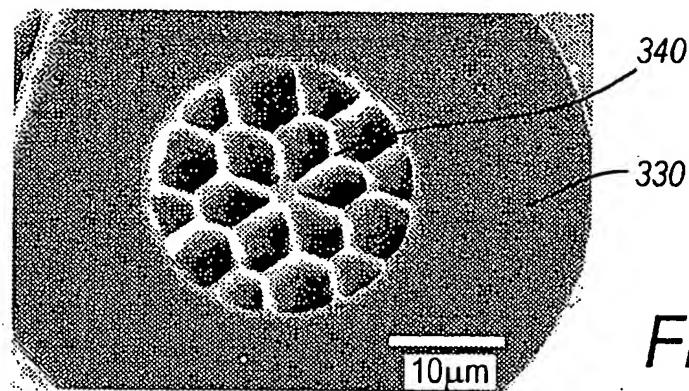
Fig.16(a)
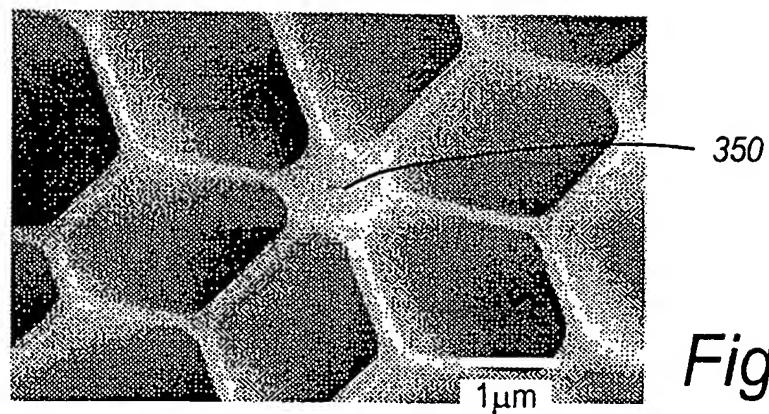
Fig.16(b)
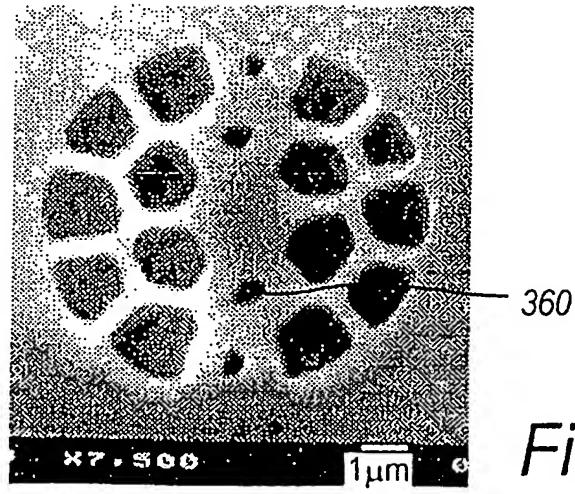
Fig.17(a)
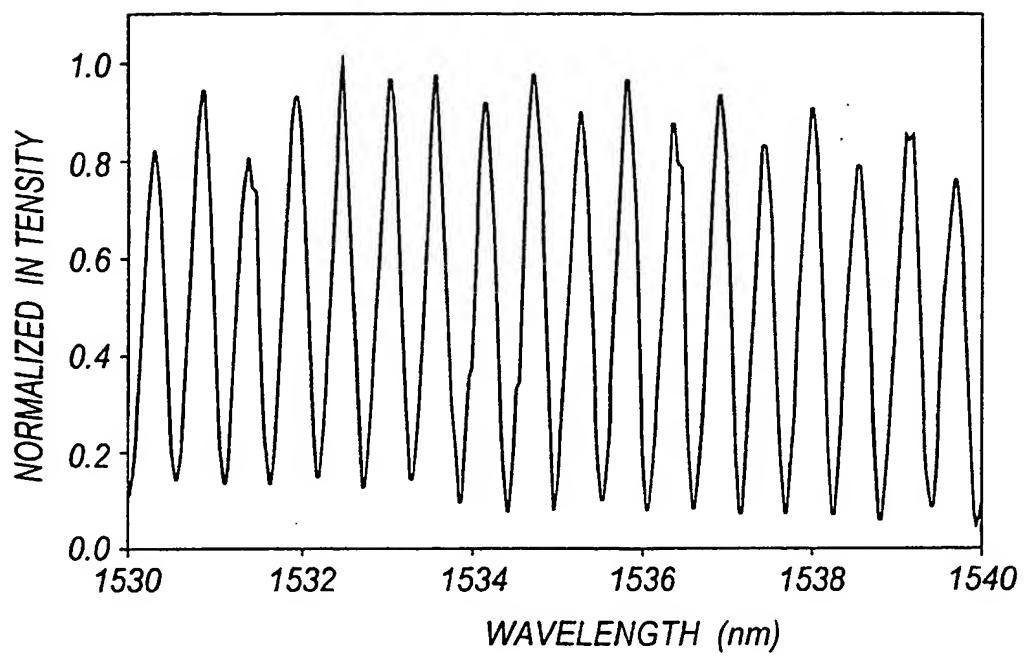
Fig.17(b)

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7   G02B6/17   G02B6/16   C03B37/075   C03B37/027

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7   G02B   C03B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 802 236 A (DIGIOVANNI DAVID JOHN ET AL) 1 September 1998 (1998-09-01) figures 1,2,5 column 5, line 6 - line 67 column 6, line 1 - line 67 column 7, line 1 - line 54 ---	1,2,5,6, 8,10,20, 37
A	US 4 551 162 A (HICKS JR JOHN W) 5 November 1985 (1985-11-05) column 3, line 21 - line 68 column 4, line 1 - line 68 column 5, line 1 - line 40 figures 1-7 --- -/--	1,17,20, 37

[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 June 2000	29/06/2000

| Name and mailing address of the ISA
European Patent Office, P.B. 5818 Patentlaan 2
NL – 2280 HV Rijswijk
Tel. (+31–70) 340–2040, Tx. 31 651 epo nl,
Fax: (+31–70) 340–3016 | Authorized officer

Mathyssek, K |

Form PCT/ISA/210 (second sheet) (July 1992)

1

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 520 653 A (HUGHES AIRCRAFT CO) 30 December 1992 (1992-12-30) column 4, line 18 - line 58 column 6, line 51 - line 58 column 7, line 1 - line 58 column 8, line 1 - line 14 figures 1,2,4 ---	1,2,8, 20,37
A	US 3 516 239 A (FUKUDA KENJI ET AL) 23 June 1970 (1970-06-23) column 3, line 12 - line 75 column 4, line 1 - line 65 claims 1,10; figure 1 ---	1,20,37
A	US 4 127 398 A (SINGER JR JOSEPH) 28 November 1978 (1978-11-28) column 7, line 4 - line 68 column 8, line 1 - line 68 column 9, line 1 - line 32 figures 10,12-14 ---	1,20,37
A	US 5 309 540 A (CHARASSE MARIE-NOELLE ET AL) 3 May 1994 (1994-05-03) the whole document -----	1,20,37

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 5802236	A	01-09-1998	EP	0810453 A	03-12-1997
			JP	10095628 A	14-04-1998
US 4551162	A	05-11-1985	NONE		
EP 0520653	A	30-12-1992	US	5155792 A	13-10-1992
			JP	5264828 A	15-10-1993
US 3516239	A	23-06-1970	DE	1669544 A	16-06-1971
			FR	1518103 A	28-06-1968
			GB	1169106 A	29-10-1969
			NL	6703905 A	18-09-1967
US 4127398	A	28-11-1978	NONE		
US 5309540	A	03-05-1994	FR	2683053 A	30-04-1993
			EP	0540386 A	05-05-1993